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13. ABSTRACT *(Maximum 200 words)*

An optical implementation of what is known as a "supervised learning" algorithm was implemented with volume photorefractive holographic medium and a spatial light modulator. We investigated how one could apply neural network principles to temporal information using photorefractive media. For this purpose, the tranfer function and impulse response of photorefractive two-beam coupling amplifiers was derived and experimentally verified. As part of the investigation on temporal processing of information, we built and demonstrated a fiber-optic acoustic transducer for audio sound processing. The sound spectra generated by the transducer were stored in a volume holographic medium. The stored sounds were used to recognize identical or similar sounds in real time.

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OPTICAL HIDDEN LAYER NETWORKS

FINAL REPORT

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U. S. ARMY RESEARCH OFFICE

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Final Report

Optical Hidden Layer Networks

A. Statement of the Problem

This research focused on several aspects of information processing using photorefractive systems based upon neural network principles. In many ways real-time holographic media seem ideally suited to neural network implementations; the question is, how well in fact can one design and control the behavior of these media to obtain certain tasks. The performance of simple supervised learning algorithms, which are popular in the neural network community, are one means of comparing implementations. One of our task was to devise and implement such an algorithm with photorefracitive media. Also of interest are dynamic neural networks capable of processing temporal information for such tasks as speech processing, sonar processing, and so forth. The question is, what is the best way to transduce an acoustic signal onto an optical one. Finally, once one obtains the acoustic signal, to processes that signal holographically one needs to understand how hologram formation dynamics can be used to advantage. In this regard, the dynamical properties of photorefractive two beam coupling needed to be characterized.

B. Summary of Most Important Results

We implemented what is known as a "supervised learning" algorithm with a photorefractive holographic medium and a spatial light modulator. We investigated how one could apply neural network principles to temporal information using photorefractive media. As part of the latter investigation, we built and demonstrated a fiber-optic acoustic transducer for audio sound processing. The sound spectra generated by the transducer were stored in a volume holographic medium. The stored sounds were used to recognize identical or similar sounds in real time. In the following sections we describe the most significant aspects of each portion of the work.

B.1. Using volume hologrphic media for neural network learning

Perhaps the most attractive feature of photorefractive materials for imbedding neural networks is that they are dynamics holographic media that function at very low light power levels. By the very nature of the holography, information can be stored and read in a parallel fashion. Thus, our first tasks was in principle a very simple one, as shown in Figure 1. A liquid crystal spatial light modulator, driven by a computer, imposed one dimensional spatial information onto a light beam which was split into two portions. The two light beams intersected in photorefractive lithium niobate. A shutter controlled the state of one of the beams (on or off). We will call these two beams A and B with the shutter controlled one being B. With B in the off state, a video camera read the intensity of light scattered from beam A by the hologram. The camera's output was recorded by a computer. This data could be manipulated and used to determine some new patterns to be imposed on the liquid crystal modulator.

The object of this experiment was to perform what is known as Adaline learning on a set of input vectors. In this task, one has a desired mapping between a set of input vectors $\{A\}$ and another set $\{B\}$. The system is to learn this mapping by selecting a member of A, then reading the light scattered by the hologram (corresponding to the output space). Given that the output is not the desired one, there is a simple algorithm called the delta-rule from which one can generate an "error" vector to be placed on beam B. One then updates the hologram by exposing the material to the interference of input vector A with the error vector B. The process is repeated with another member of the set A, and though each input vector many times. It has been shown that under the proper circumstances, the interconnect provided by the hologram will converge so that every input A is mapped to the desired target vector B.

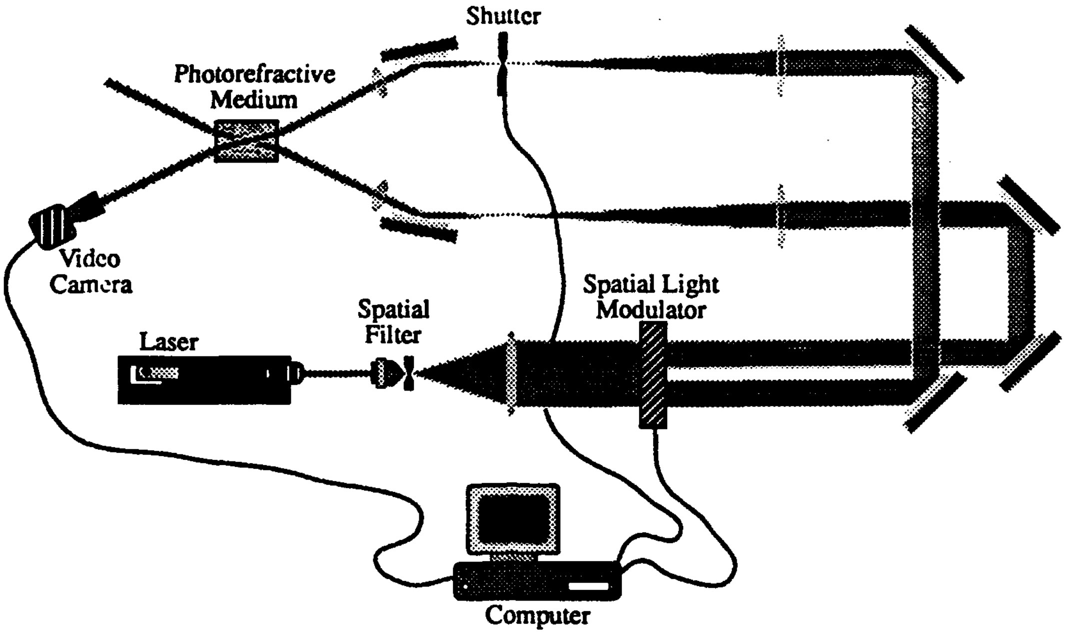

Figure 1 Schematic for holographic Adaline learning.

In the course of our experiments we found that in practice our system worked well for three input vectors, it worked acceptably for eight input vectors, but it would not converge at all for more than eight input vectors.

The primary problem was associated with the liquid crystal spatial light modulator. Its characteristics changed rather dramatically over time, and, worse, in a history dependent manner. That is, its current transfer function would depend upon what information it had recently contained. We concluded that a much improved spatial light modulator would be needed for further progress.

In absence of better spatial light modulator, we concluded that one should avoid a literal translation of a given model to its opto-electronic implementation. Instead, one should try to use the dynamics available in photorefractive material to realize the functional behavior of some of the more biologically motivated models. In particular, this led us to consider models of acoustic processing, discused in section 4.

B.2.Theory of the holographic two-port operator

Despite the experimental difficulties with holographic learning, we proceded to investigate theoretically the kinds of problems likely to arise from the holographic process itself. From the efforts to understand the formation of superimposed holograms in photorefractive materials we have formalized a particularly important notion: Formally the hologaphic crystal can be treated as a two-port linear operator. If one treats the material as a collection of discrete elements the operator takes the form of a matrix; for the continuum case the operator is expressed as a scattering kernel. It has been shown that the matrix elements, or the kernel, can be calculated knowing the holographic grating everywhere within the crystal. This is a very powerful approach to take when investigating the output of a holographic grating illuminated with optical fields. It is particularly powerful when applied to computer modeling of the optical systems. In conjunction with the modeling, the first version of an object-oriented computer program designed to run on a DECstation 3100was put into operation. This program uses the matrix element approach to the photorefractive gratings to simulate the behavior of optical circuits composed of these media.

The theoretical treatment allows one to see how the noise and error terms during hologram formation come into being. From here, one can determine how these effects play upon holographic learning, and how problems might be ameliorated.

B.3.Impulse response and transfer function of photorefractive two beam coupling

As we discuss further in section 4. one of our goals was to understand how one could implement neural models of acoustic signal processing using the dynamic of photorefractive materials. In this regard, the time-dependent behavior of two-beam coupling needs to be understood. Perhaps the most significant advance in this investigation was the derivation of the Laplace transfer function of two-beam coupling in the undepleted pump regime. The transfer function is a very unusual one. From the transfer function it has been possible to obtain a closed-form expression for the impulse response funciton of the two-beam coupling amplifier.

The impulse response function is characterized by a delayed pulse response. The delay time is a function of pump beam intensity. Therefore, one can program a delay using the pump intensity as the parameter.

We performed a series of experiments measuring directly both the transfer function and the impulse response of two beam coupling in barium titanate. In principle the two sets of experimental data for the impulse response and transfer functions should be LaPlace transforms of each other. We found that the *shapes* were consistent with this expectation, but that they differed quantitatively by a factor of from two to four. After some investigation, the discrepancy was recognized to be a manifestation of beam fanning (stimulated scattering). For our purposes, the quantitative discrepancy is insignificant.

The delay property of the photorefractive two beam coupling impulse response has interesting implications for time domain optical neural networks. In particular, we have studied a speech processing network demonstrated by Hopfield and Tank that uses "learned" time delays to recognize speech. Hopfield and Tank use a (simulated) transmission line that causes pulse spreading as well as delay. It happens that the two-beam coupling amplifier has exactly this kind of impulse response function --the longer the delay, the wider the pulse, but the area under the response remains constant. Furthermore, the intensity dependence of the impulse response allows us to program the delay.

B.4.Acoustic transducer

As a front end to an acoustic signal processor it is convenient to obtain a Fourier transform of the incoming signal. Although there are a number of digital electronic integrated circuits designed to perform this task, since our processing is optical we concluded that the most efficient front end would consist of an optical transducer that directly obtained the Fourier transform of the acoustic signal. Accordingly, we built an optical acoustic signal analyzer composed of a collection of 120 optical fibers. A cantilevered optical fiber is a mechanical resonator. Its resonant frequency ω_r depends on its elastic constants and its physical size. In particular, ω_r is inversely proportional to the square of the length of the fiber. Thus an array of cantilevered optical fibers with different lengths can be viewed as a spectrum analyser. As shown in Fig.1, the acoustic transducer is made of such an array of optical fibers and a photorefractive novelty filter (1). The resonant frequencies of the fibers logarithmically sample the acoustic spectrum from approximately 100Hz to 5kHz. Sound signals are received by each fiber in the array. Laser light is injected into all fibers simultaneously and is reflected from the end of each fiber. The reflected light passes through a photorefractive novelty filter. The novelty fiter eliminates the optical carrier and leaves only the acoustically imposed sidebands. The output image is essentially a scrambled Fourier transform of the driving signal.

The fibers are clamped at one end and are free at the other; thus they are free to vibrate. The lengths are set so that the resonant frequencies of these fiber cantilevers cover the acoustic speech range of about 100Hz to 5KHz. The fibers are driven by a bridge (as in a stringed instrument) connected to a piezo element. The free ends of the fibers are silver coated so that incident light is re-

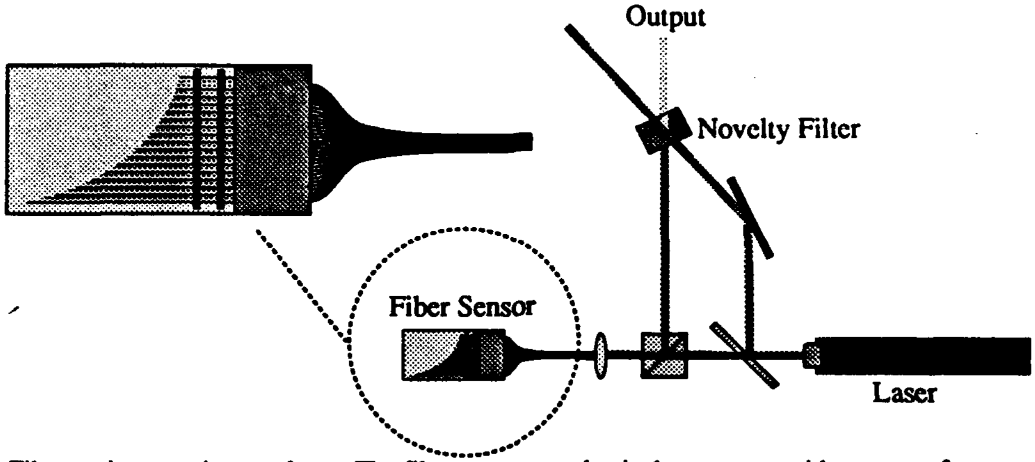

Figure 2. Fiber optic acoustic transducer. The fibers act as mechanical resonators with resonant frequency inversely proportional to the inverse square of their lengths. The reflected output of the fibers is process by an optical novelty filter, which provides the Fourier transform of the acoustic signal.

flected. Laser light propagates along each fiber, is reflected, and exits the input end. This output is then put through an optical novelty filter (see the attached figure). In steady state, no light exits from the novelty filter. When a given fiber vibrates, however, the phase of its light is modulated and an output from the novelty filter appears. In this manner a Fourier spectrum of the acoustic signal on the piezo element is obtained as a dot pattern.

To combine the transducer with a holographic optical processing system, we have designed a scheme to store sounds in a single $LiNbO_3$ crystal. The experimental set up is as in Figure 3. When a sound is received by the transducer, it generates a characteristic vibrational pattern on the fiber array and a corresponding modulation on the fiber modes. After the novelty filter, the optical carrier is suppressed, and only the acoustic sidebands are left. The "acoustic image" thus obtained is used to write a hologram with a reference beam of light. The hologram then acts as a matched filter for the sound, and allows us to recognize a previously stored sound.

The reference wave must also contain the same acoustic sidebands to write the hologram with the transducer output. In our demonstration, an electro-optic modulator (EOM) is used to provide the sidebands on the reference wave. The electro-optic modulator is used as an amplitude modulator. The direction of the output polarizer is perpendicular to the input polarization, so that the optical carrier is suppressed at the output. The electro-optic modulator and the acoustic transducer are simultaneously driven by the same sound, thus a grating is formed in the holographic crystal. By angle encoding the reference wave, one can store several holograms in a single $LiNbO_3$ crystal.

We have written two angle-encoded holograms with two sounds. Each sound has a stationary spectrum and is synthesized with five different acoustic frequencies.

C. Publications

1. M. J. O'Callaghan and D. Z. Anderson, "Multiple scattering of light within two-dimensional volume holograms," JOSA A (in press).

2. D.Z. Anderson, C. Benkert and D. D. Crouch, "Competitive and Cooperative Multimode Dynamics in Photorefractive Ring Circuits," in Neural Networks for Human and Machine Perception (H. Wechsler, Ed., Academic, Boston, in press).

3. D.Z. Anderson, C. Benkert and D. D. Crouch, "Photorefractive Systems and the Elements of Decision Making," in Optical Computing, (S. Lee and L. Giles, Ed., Academic Prss, Boston, in press).

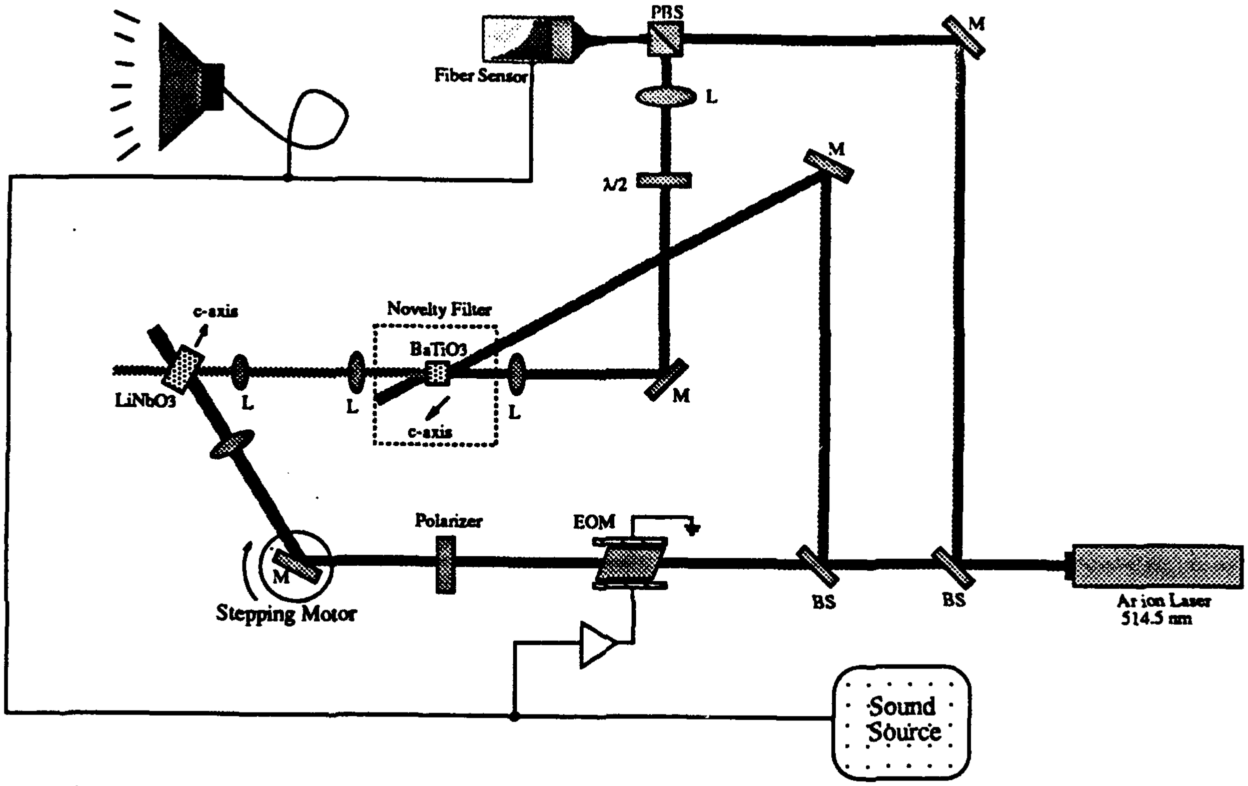

Figure3.ThestorageoftheFouriertransformofsoundsinaphotorefractivelithiumniobatecrystal,dopedwithiron,0.015%. An electooptic modulator imposes the acoustic sidebands onto the angle encoded reference beam to match the sidebands present in the transducer signal. Each sound is recorded with a different reference wave.

4. A. Hermanns, D. Lininger, C. Benkert and D. Z. Anderson, "Impulse response and transfer function of two-beam coupling amplifiers," IEEE J. Quant. Electon. (submitted).

5. G. Zhou, L. Bintz, and D. Z. Anderson, "A fiber-optic acoustic Fourier for audio sound processing," Applied Optics (submitted).

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